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The Conceptual Design of a Mach 2 Oblique Flying Wing Supersonic Transport

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Nomenclature

	Description:	dimension:
BPR	bypass ratio	
C	climb speed	m/s
CL	lift coefficient	
$CM_{0.25}$	0.25c Pitching moment coefficient	
DE	design empty	
h	altitude	m
L/D	lift-to-drag ratio	
M	Mach number	
mgg	maximum gasgenerator massflow	kg/s
OE	operating empty	
OPR	overall pressure ratio of compressor	
S	wing planform area	m^2
s	distance	
T	Thrust	N, kgf
t/c	thickness to chord ratio	
TET	turbine entry temperature	K
tmax	maximum external thickness	m
VEAS	equivalent airspeed	m/s
Wp	payload weight	kgf
Wto	takeoff weight	kgf
α	angle of attack	deg
σ_{max}	limit material strength	N/mm^2
θ	angle of pitch	
Λ	0.25 chord wing sweep angle	deg
ψ	specific thrust	s
η	overal engine efficiency as used in Brequet formula	

indices:

max	maximum
n	normal to the leading edge
to	takeoff

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Abstract

This paper is based on a performance and economics study of a Mach two Oblique Flying Wing transport aircraft that is to replace the B747B. In order to fairly compare our configuration with the B747B an equal structural technology-level is assumed.

It will be shown that the Oblique Flying Wing configuration will equal or outperform the B747 in speed, economy and comfort while a modern stability and control system will balance the aircraft and smooth out gusts.

The aircraft is designed to comply with the FAR25 and FAR36 stage 3 noise regulations.

The present design study was carried out for the Computational Fluid Dynamics division of NASA-AMES Research Center.

Introduction

A conceptual Oblique Flying Wing Supersonic Transport Aircraft, from now on referred to as OFW, was first proposed by Dr. R.T. Jones in 1957 and by Mr. Lee of Handley Page (ref. 1,13). Problems with the stability and control of the configuration prevented further development at that time.

In the spring of 1987 the author and Dr. Jones met in Los Altos and discussed its reintroduction in view of the emerging technology of artificial stabilization.

The oblique Supersonic Flying Wing as presented in fig.1 synthesizes three of the most promising orphans in aeronautical history:

1) The oblique wing: Proposed for the first time shortly after WWII by Robert T. Jones, this adaptive wing concept provides high lift-to-drag ratios at all speeds and therefore greatly increases the low-speed performance for aircraft designed at high speeds.

2) The flying wing and distributed load aircraft: Around the WWII period serveral designers like Lippisch and Burnelli, Northrop saw the advantages of flying wing aircraft. Such aircraft had higher cruise lift-to-drag ratio's and lower empty weights due to the reduced wing bending moment, however stability and control considerations prohibited their further development (ref. 4)

3) The supersonic passenger aircraft: The supersonic passenger aircraft was in the focus of public attention during the sixties and mid-seventies. However, the economic failure of Concorde and the SST led to the abandonment of the idea of commercial supersonic flight, even though everyone recognizes the importance of reducing the current longhaul flighttime.

Description of the baseline design

The baseline configuration accommodates 462 passengers and 16 cabin crew who can be seated at a 35" pitch, twelve abreast. Apart from the cylindrical shell the the interior resembles that of a wide body airliner with an average aisle height of 1.95m (Fig. 1).

In view of possible claustrophobia among the passengers, windows are installed in the nose (Figs. 2,3). The emergency exits are located in the nose and trailing edge side of the passenger cabin. These emergency exits can be reached by access ramps that lead to the top of the wing. It remains to be investigated whether such a solution is adequate. Two entrance doors are fitted into the wing nose.

Another deviation from the wide-body standard is the cockpit. In view of the oblique wing characteristics it does not make sense to design a protruding cockpit structure as suggested in ref. 13. Instead, space is provided on the left end of the cabin to house two pilots (Fig.3). The pilot will have good visibility during approach and climb. However his field of vision is 70^{o} left 70^{o} right instead of 135^{o} left 30^{o} right as is recommended by the FAR 25.777.

One of the classical objections against the flying wing, namely that it does not have stretch potential, is not true for our baseline configuration. We can simply add center cabin sections of the wing's maximum thickness. It can be easily shown that, in doing so, we will even increase the L/D of the configuration.

The wing has an elliptic planform with a near elliptic spanwise thickness-to-chord distribution, resulting in minimum wave drag for a given volume (ref.3).

In order to obtain an elliptic spanwise lift distribution, the elliptic wing planform must have a uniform distribution of lifting pressures, even at large angles of yaw. This was be realized by giving the wing some upward curvature. The curvature was calculated with an inverse potential flow code. For our configuration the desired curvature was given by an upwards tip deflection of 2% of the semi-span.

Under the initial cruise conditions of M2 and 16000m, the no-drag rise CL_n for maximum L/D would be 1.0. New airfoils (such as the OW-7-10) do reach these high lift coefficients during supersonic cruise, but Kuchemann (ref. 10 pp107) and my own optimization show that a value of CL_n=0.7 gives the maximum payload to maximum takeoff weight ratio. Apart from this it must be realized that a flying wing can never have the higly loaded trailing edge that is required to reach these high CL's because of the high pitching moment.

To achieve this lift coefficient with minimal drag and a low cabin floor incidence the resultant lift force during cruise must be as far back as the artificial stability and control system allows. Since (on average) this value lies at 32% of the mean geometric chord the, amount of camber will have to produce a $CMn_{0.25}$=-0.048 at cruise. To balance the configuration the center of gravity position is shifted to this exact value by a fuel trim system.

Because the airfoil will have to seat passengers comfortably the maximum section t/c ratio will have to be at least15%. Fig. 2 shows the 16% thick wing center section as it was designed using ARC2D, a two-dimensional Navier Stokes solver written by T. Pulliam.

The OFW has a conventional monocoque and honeycomb structure using the aluminum alloy RR.58-AU2GN developed for Concorde which showed good maximum stress and fatigue qualities at high temperatures (ref. 7) We can expect an 15000 hour increase in airframe life (with respect to Concorde's 45000 hpirs) by the limitation of the Mach number to two, which reduces the equilibrium skin temperature from 130°C to 100°C/373K.

To enable the structure to carry the loads of pressurization while maintaining a near unobstructed 'wide body' cabin , ceiling to floor connectors are placed at 3m (10ft) intervals. Such connectors could be placed at each side of the center seat block. Since the toilets and the galleys also perform a connector function, only 16 added connectors are necessary. In an analysis carried out by the author it was found that such a structure of supported AU2GN-honeycomb panels would be no heavier than a multibubble faired over

conventional design, but would offer a far more spacious and flexible cabin layout.

The nacelles can be pivoted over a 35° range and are distributed optimally along the span. In view of the limitations of the artificial stability and control system the nacelles had to be placed as far forward as possible, while synergistics, cabin noise and aerodynamic considerations dictated the placement outside the passenger cabin. To increase one engine-out yaw control and to minimize the wave drag and wing stress, the engines were podded in four nacelles.

The configuration is powered by four 250KN engines of conventional design with a maximum core massflow of 187 kg/s. These characteristics could be obtained from a refanned Rolls Rocye Olympus or a double scale GE F101/110. The inlets are of the two-shock three-dimensional mixed compression type.

The undercarriage has six legs with four 40"x14" tires each. Even though we have a distributed load undercarriage, the present layout still has a rigid runway LCN of 79. In view of the short takeoff field length, we could consider redesigning the legs so the OFW could operate from the same runways as the B757. In this way, we would increase the number of possible destinations by a factor of five.

Table 1 will give more detailed technical information of the OFW design.

Optimization of the Baseline Design

To size the wing and the powerplant the author has chosen the Wp/W_{to} fraction as optimization criterion. In ref. 15 it is considered as the most important indicator of aircraft economy. But we also have to recognize that there are constraints to our configuration, the most important of which are :

a- **Specification;**

Basic B747-100B: The configuration has to accommodate 450+ passengers over a 9000km range at M2. The most important derived constraint for the OFW is the minimum required height dimensions of the cabin so we can seat the passengers. An OFW as described in the previous chapter would have to have maximum center thickness of least 2.29m.

b- **Technology (database) availability;**

Both limited access to information and actual limitations of the available technology can limit our optimization process.

The following technology levels were assumed readily available today:

- **Structural**: Conventional AU2GN honeycomb, σ_{max}=400N/mm², able to withstand design maximum Mach number of 2, design Maximum Dive Mach number 2.1, and a maximum equivalent airspeed of 226 m/s for an airframe life of 60.000h or more.

- **Aerodynamics**: A $(t/c)_{max}$=15% for a CLn=0.7 and Mn=0.7 are the maximum values that can be used for a trimmed OFW with minimum drag rize.

- **Powerplant**, conventional BR=1 fan design with mixed gasflow, TET 1700K, OPR=11, with contemporary isentropic efficiencies. A gasgenerator airflow around 185 kg/s if we assume to use a refanned RR Olympus.

c- **Airworthiness requirements;**

The aircraft has to comply with the FAR 25 airworthiness requirements and the FAR 36 stage 3 noise regulations. A direct result of the compliance with the noise regulations is the impossibility to use a BPR smaller than 1, even if variable cycle engines are used.

Using the above criteria we select the optimum wing geometry. Contrary to conventional wing planform sizing, it is unnecessary to choose the optimum area of the wing planform. It is not hard to understand that the minimum wing area that can provide seating for the passengers ($S=1461m^2$/ $V=1673m^3$) is the optimum.

We are now left to choose the wing ellipse ratio and the powerplant size. Fig. 4 shows the iso-Wp/Wto lines for varying T/W and ellipse ratios. Within the constraints, an ellipse ratio of 8, and a T/W of 0.34 gives the optimum.

At start cruise the powerplant would have to have a specific thrust of 40 s for BPR=1. If we look at Fig. 5 we see that this can be achieved by taking different combinations of TET and OPR. As can be inferred from the graph the maximum Wp/Wto-ratio occurs with a TET=1700K and OPR=11. Not surprisingly, an OPR of 11 is also used in other supersonic engines.

For this combination the subsonic and supersonic propulsive efficiencies are high, while the turbomachinery (thrust) losses are low, maintenance costs acceptable, and engine weight low.

Aerodynamic and Operational Characteristics

In Fig. 6 the effects of Mach number variation of maximum L/D and engine efficiency are shown. Aerodynamic calculations were done using J H B Smiths model (ref.3). Additional drag terms from engine and tailplane installation were included in the model. In Table 2 the drag breakdown for Mach 2 cruise is given. The maximum aerodynamic efficiency at cruise is above 10, while at subsonic speeds values above 20 can be reached.

The weight breakdown for the transpacific range and design payload (462pax / 9000km) is given in Table 3. Notable is the low structural weight.

At takeoff the wing angle of incidence is set (at about 4.5^{o} normal to the leading edge) by adjusting the gear. Minimum allowable wing sweep is limited by the vertical tailvolume.

The takeoff and climb performance is better than the B747's. At MTOW the aircraft requires a balanced field length of only 2000 m and reaches the initial cruise altitude of 16000 m and M2 in about half an hour.

As can be seen in the flight envelope (Fig. 7), climb and descent are constrained by the following considerations:

Minimal Equivalent Airspeed is not allowed to drop below 64 m/s EASn to assure safe handling during heavy gust.

Maximum Equivalent Airspeed does not exceed a value for which n>2.5g, when FAR25 maximum gusts would occur. This value corresponds with the condition for which the ride quality according to ref. 14 is adequate. If this boundary is observed, the chance to encounter a 6 m/s2 acceleration due to gust is only 10% per flight.

Maximum Available Thrust between M 1 and M 1.8. At these Mach numbers 12% additional thrust is needed.

Within these limitations, a trajectory was determined that would lead to the fastest arrival at cruise height and speed. The OFW uses 22% of the total fuel available for acceleration and climb (only half of what Concorde needs.)

Takeoff was established within the FAR25 regulations. To conform with the noise regulations the baseline RR Olympus has a bypass flow ratio of 1 and the turbine has been lengthened accordingly also, the afterburner has been omitted and takeoff is performed at 75% of the maximum thrust. This offers the possibility of weight savings, since we could now rate the engine for climb and downrate the engine at takeoff.

Emissions and ozone-layer depletion can be reduced significantly in comparison to the old Olympus engine, when we use the newest GE technology as it was proposed in their variable cycle engine concept. A maximum sonic boom overpressure of 70 N/m^2 due to supersonic flight was found, a value comparable to Concorde's even though the aircraft is much heavier. However, since the performance characteristics of the aircraft allow economic transportation at the boomless supersonic Mach number of 1.2, so there is no need for Mach 2 overland flight.

Fig. 8 gives the payload range diagram and the estimated direct operating costs for the 1986 situation. The direct operating costs we calculated using the definition of DOC of ref. 16 and the methodology of refs. 17 and 18. In Table 4 a breakdown for the DOC is given.

Stability and Control

In Fig. 9 an overview of the stability and control of an oblique flying wing is given.

Stability and control around the X and Y axis is provided by a 10% multisegmented tailing edge flap similar to the one proposed by NASA for the DLC-cargo transport (ref. 4). Segmenting the trailing edge flap increases the reliability of the system and allows roll-control.

Such a flap system could put the neutral point as far back as 37% of the mean aerodynamic chord at OEW, and smooth out any gust peaks. It will also allow us to use a more cambered wing and a higher design lift coefficient.

The artificial stability and control system that controls this flap uses a standard PID (ref. 9) controller. This controller relates the angle of pitch theta and its first and second time derivatives to an optimum flap deflection. In practice, such a system could get very accurate predictions of the aircraft pitch from a Honeywell lasergiro. Alternatively an equally good system could be designed using the angle of attack as control value.

Fig. 10 shows the predicted rearward stability limits when the PID-feedback system developed by the author is in place. The dynamic model was only quasi-3d and accounts for non-linearities such as aerodynamic lag. The dynamic stability limit is set by the 20.13 (66ft/s) gust at minimum control speed. As can be seen, the system is more sensitive to step gusts than to a FAR25(1-cosine) gust. To avoid risks, the rearmost center of gravity position is located behind the step gust's neutral point.

The stability limit moves forward with increased configuration weight because the required flap deflection will go beyond flap stall for the same gust in 1-g flight. As the aircraft weight increases so does "1-g" CL and downward flap deflection reducing the control authority for upward gusts. Aircraft response at A,B is depicted in Fig. 11a, b.

In the summer of 1987, Steve Morris (a graduate student of prof. Ilan Kroo at Stanfords' University Aero-Astro department) flew a model of an unswept flying wing with such an artificial stability augmentation system (Fig. 12a, ref. 19) The model had proven dynamic stability for a center of gravity position at 32% of the mean aerodynamic chord (Fig. 12b). The measured flap deflection with stick command input from a flight test is given in fig. 12c. Since this configuration is much smaller flap frequenties had to be a lot higher than for our supersonic transport.

The configuration has three 'all-flying' vertical planes mounted on the engine pivot. The combined size of the vertical tailplanes is set by the one engine out condition at takeoff. To assure static stability around the z-axis we have two rear vertical tailplanes.

For sideways maneuvering the inboard front and rear vertical tail will have to be loaded equally to balance the configuration around the z-axis. The present configuration can cope with CY's up to 4% of CL by vertical tail deflection alone. This also enables the configuration to make sidewind landings without a bank angle. For higher CY's some bank may be used.

Vortilons may be used to control the boundary layer at the high angles of attack that may be produced during heavy gust conditions.

Conclusions

Excluding qualities that apply to any transport aircraft, an Oblique Flying Wing transport should preferably have:

GEOMETRY

a1- **A minimum size of 1100m^2.**
If the flying wing is to accommodate passengers a minimum size is required. A minimum size oblique wing would seat 350 passengers have a planform of 1100m^2, an ellipse ratio of six and a Wp/Wto of 12%. The OFW as presented here seats 500 passengers, is slightly larger and has a 20% higher Wp/Wto.

a2- **Pivoting nacelles**, that are place along the leading edge to move the center of gravity as far forward as possible in view of c1. The outboard panels are the best location primarily to reduce cabin noise.

a3- **Vertical control surfaces each side of the span** in view of c1

AERODYNAMICS

b1- Operation at a constant moderate normal design lift coefficient of **CLn=0.7 Mn=0.7**. Higher values are not possible since they cannot be trimmed at the constrained (by c.) location of the center of gravity.

b2- **A limit on the inclination of the passenger cabin** during operation to no more than 4.5 degrees (take-off) and 3 degrees cruise.

STABILITY AND CONTROL

c1- **A limit on the rear location of the center of gravity** of 34% of the root chord set by the implementation of 12% flap/chord ratio trailing edge flap driven artificial stability and control system. Such a system should assure good handling characteristics and smooth out any gust.

c2- **Ability to trim CY** without excessive drag by deflecting the vertical tailplanes and the rotating the engines.

c3- A **fuel trim system** to bring the center of gravity to the position that b1 and b2 can be achieved without violating c1.

STRUCTURE

d-1 An aluminum honeycomb cabin, that is supported by **floor to ceiling connectors** to minimize weight which provides maximum space and payload flexibility.

The oblique flying wing SST, as presented in this paper combines low structural weight, high aerodynamic Lift-to-Drag ratios from subsonic speeds to Mach 2.

As compared to contemporary subsonic aircraft of the same size its operational characteristics are superior. The aircraft can fly at the same holding speeds as today's subsonic transports, and requires only half the takeoff field length.

The total cost of development of the aircraft is going to be higher than of any other aircraft sofar (around 10 billion ('86)USD), but due to the high blockspeed the direct operating costs of the aircraft are going to be comparable to the B747's.

It is therefore proposed that further research is done to validate the results presented in this study and to expand the database on oblique flying wing configurations.

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Table 1 Technical describtion

External dimensions:

Wing span	122.00	m. [400']
Wing chord root	15.25	m. [50']
Wing aspect ratio	10.16	[unyawed]
Wing sweep in cruise	72.5	deg
Aspect ratio in cruise	1.06	
Height overall	10.7 m.	[35']
Cabin max. external thickness	2.30 m.	[7.5']
Vertical tails: (3)		
span	5.06 m.	[16.6']
Aspect ratio	0.85	
taper ratio	0.25	
leading edge sweep	60	deg.
Wheel span	44.0 m.	[144']
Wheel track to/landing	35.00m.	[115']
Wheel base	8.52 m.	[unyawed]
Wheel size	40x14"	(6 legs)
Passenger door (2 in lower floor nose)		
Height	2.00 m.	
Width	1.00 m.	
Emergency exit (13 in cabin nose and rear of cabin)		
Height	0.90 m.	
width	0.50 m.	
Baggage door (2 in floor baggage holds)		
Height	1.60 m.	[5.25 ft]
Width	3.20 m.	[10.50 ft]

Nett internal dimensions:

Cabin:

Length incl. galley toilet and baggage compartment) 62.0 m. [206 ']

Length passenger cabin	44.4 m.	[148 ']
Maximum width	7.2 m.	[24 ']
Maximum height	2.10 m.	[6'9"]
Floor area pax.cabin	316 m^2.	[3400 sqft]
Volume passsenger cabin	550 m^3.	[5900 cuft]
Left cargo hold	51 m^3.	[8 containers]
Right cargo hold	57 m^3	[9 containers]
	container:	10'x5'x4''

Areas:

Wing	1461 m^2.	[15,700 sqft]
Vertical tail area's/each	30 m^2.	[322 sqft]

Weights:

Maximum takeoff	304200	kgf.[676,000 lbs]
Maximum operating empty	130200	kgf.[289,000 lbs]
Harmonic payload, 35"pitch	43700	kgf.[97,0000 lbs]
	462pax	no cargo
Maximum payload	67300	kgf .[150,000 lbs]
	540pax	16ton cargo
Harmonic fuel	114000	kgf.[273,000 lbs]
Reserve fuel	8900	kgf.[19,000 lbs]
Maximum fuel	139400	kgf.[310,000 lbs]
Maximum landing	189000	kgf.[420,000 lbs]

Engines:

4 turbofans (could be refanned modernized RR OLYMPUS) with the following characteristics:
mixed flow, condi-nozzle, 3D 2 Shock inlet

maximum gasgenerator massflow	187 kg/s
BPR	1.0
TET cruise	1700 K
Compressor face Mach number	0.55
OPR	11
Thrust static max.	250 KN
Thrust TO max. (FAR 36stg3)	182 KN

Thrust @ V2	165 KN
Thrust @ 15800m, M2	74 KN

Performance:

max cruise mach number:	Mach 2	(2124 km/u, 1327 mph)
start cruise altitude:	15,800 m.	[52,000']

Harmonic Range with IFR reserves at max cruise speed:
9000km [5625 miles]

Long range overland cruise speed
Mach 1.2 (1250 km/u)

Takeoff procedure:	zoom-start, no flaps wing at 4.5° incidence
Balanced field length @mtow	2020 m.
$\Delta\gamma_2$(one engine out10.5 m)	6.9%
Rigid runway LCN	79
V2	84 m/s
Vmin.contol @mtow	<80 m/s (at 37° sweep)
Sideline noise:	104 db EPNl
Max. climb speed (SL)	34 m/s
W/Smax	2.0 KN/m^2
T/Wmax	0.34

Max. sea-level sonic boom pressure rize at 16000m and Mach 2:
67 N/m2

Table 2: Weight breakdown for the transpacific range (9000km)

group	item		weight	xcg_n	Sx	xcg/mgc_n
Structure						
(1)	midsection (pax. cabin)		25.172	5.60	140.963	
(2)	outboard panels		21.112	4.40	92.893	
(3)	flaps		3.370	13.00	43.807	
(4)	vertical tail		1.900	4.50	8.550	
(5)	gear		12.20	5.60	68.320	
(6)	surface controls		1.24	7.78	9.647	
(7)	nacelles (4).incl. pivot		11.90	0.80	9.520	
	total:		76.89		373.701	
Powerplant(4 dry engines, 250KN each)						
	gasgenerator:	4 x 3.28	13.12			
	fan:	4 x 0.81	3.24			
	jetpipe:	4 x 0.22	0.88			
	fuel sytem:		0.74			
	total		17.98	0.80	14.384	
Systems+equipment						
	apu		0.305	8.38	2.556	
	instruments		2.480	2.00	4.960	
	hydraulic+pneumatic		2.090	5.80	12.120	
	electrical		2.220	4.19	9.302	
	furnishings+equipment		16.60	4.70	78.020	
	airconditioning+anti-icing		1.78	3.96	7.049	
	otal		25.48	5.80	114.011	
	DEW		120.35		502.095	0.281
Operational items						
	crew provisions		1.21	3.90	4.703	
	passenger supplies		6.93	4.70	32.571	
	residual fuel+oil		0.50	3.80	1.911.	
	miscellaneous		1.20	6.80	8.184	
	total		9.84		47.370	
	OEW		130.19		549.465	0.285
Payload						
	passengers		35.57	4.70	167.198	
	luggage		8.32	4.70	39.085	
			174.081		755.748	0.295
Fuel						
(1)	reserve fuel (trim)		9.20	10.0	92.00	
			183.281		847.748	0.319
(2)	tripfuel		121.000	3.8	459.800	0.291
MAXIMUM TAKEOFF WEIGHT			304.281 kgf			

---->Next page:Methodology

Methodology:

Structure

(1) Maximum load due to 0.7 bar overpressure at cruise altitude
Weight calculation on the basis of 0.05m AU2GN aluminum honeycomb with floor-ceiling connectors every 10ft.
and ref 12. Appedix D weight penalties flooring, mounts,windows

(2) ref 12 Appendix C for 4 mounted engines+ spoilers, speedbrakes

(3) ref 12 Appeddix C 10% flap chord 12 deg. max deflection V_f=130m/s

(4) ref 12 pp 281 26 kg/m2 specific tailplane weight

(5) ref 12 pp 283 4.5% mtow

(6) ref.12 pp 283 284 cockpit controls,autopilot,system controls

(7) ref 12 pp 284 pivot=0.2*mass engine

Powerplant

(1) ref 12 pp 130

Systems, Equipment and Operational Items and Payload

ref 12 pp 286-295 for high subsonic long range aircraft with economy layout comparable to B474
payload:1 pax 77kg. + 18 kg luggage

Fuel

(1) ref. 15 with an equivalent range increment of 900km

(2) Breguet formula for cruise at start cruise conditions and calculation of fuel used in climb and manoeuvering for this configuration

Table 3 Drag breakdown at cruise: M=2.0 16.000m.

Component		Drag Coefficient
Fiction	(1) Wing	.00329
	Tail	.00018
	Nacelle	.00019
Wave	(2) Wing/Tail	.00133
	(3) Engine installation.	.00024
	(4) Roughness	.00021
Lift	(5) wave/induced	.00181 @CL=0.071
Total Drag Coefficient		.00725
$(L/D)_{start\ cruise}$		**9.80**

Method:

(1) Strip:Prandtl Schlichting equation fully turbulent(Ma,Pr,Re)
Form drag according to ref.12 pp 499-501,transition 5% le

(2) Linear supersonic volume dependent wave drag based on optimal planform (method ref. 3.)

(3) application of Wards transfer rule.
Volume=Nacelle+Compression Air,Nacelle length;
KO_{nac}=1.5, Volume=Nacelle+Compression Air;
based on "A discussion of selected aerodynamic problems on integration of systems with airframe on transport aircraft."by Walter C. Swan, Boeing Company
Spillage drag=1.2*A_{spil}/S, Note: cruise is spillage free

(4) Skin Roughness: grain=17μm (NACA 4183 method)
flap drag:(D. Fiecke: "Die Bestimmung der .... fuer entwurfszweke" DVL 1956
Systems drag: (S.F. Butler: AGARD CP124 1973)
Surface imperfections (K.R. Czarnecki e.a. NACA TN 4299)

(5) Minimum lift dependent drag of an elliptic oblique wing with full leading edge suction according to R.T. Jones(ref. 3)

Table 4: Economic comparison between the OFW and the B747

-------1984 Conditions--------

OFW Development cost of the airframe:	8.40 G$
OFW Development cost of the engines:	1.97 G$
OFW unit price for a break-even number of 200:	409 M$
B747 price in 1984:	103 M$
Cost of fuel:	85 cts/gallon
Range:	9000km/ 5.6h blocktime
Number of passengers:	OFW: 462 @34"pitch
	B747:452 @34"pitch
Block-to-blockspeed	1599 km/h
Utilization 747 and OFW:	blocktime=4500 h/year
Depreciation:	14 years to ten percent
Insurance:	1% of aircraft price

----------OPERATING COSTS----------

Item	OFW/nbe=200 (Vb=1599km/h)		B747 (ref.11) (Vb=755km/h)	
	$/km	$/blockhour		
flightcrew	0.46	750	1.00	750
fuel/oil	3.61	5774	3.60	2719
ownership/insurance	3.76	6020	2.27	1896
Maintenance:				
Airframe	0.35	562	0.34	255
Engine	0.59	936	0.30	226
Burden	0.18	283	0.52	395
DOC	8.95		8.03	$/km
DOC/km	1.93		1.78	$cts/paxkm
additional fare:	0.62		0.00	$cts/paxkm

As expected the cost of ownership of the aircraft + parts is much higher for the OFW than for the B747 while the other cost items are a bit reduced which results in a Direct Operating cost just slightly above the B747's.
We have calculated the acceptable increase in fare by using the average US income of $9,00/h as the passengers opportunity cost of time.

-----MAXIMUM ANNUAL PRODUCTION-------

OFW	3.35e9 passenger kilometers @10% higher fare
B747-100B	1.53e9 passenger kilometers

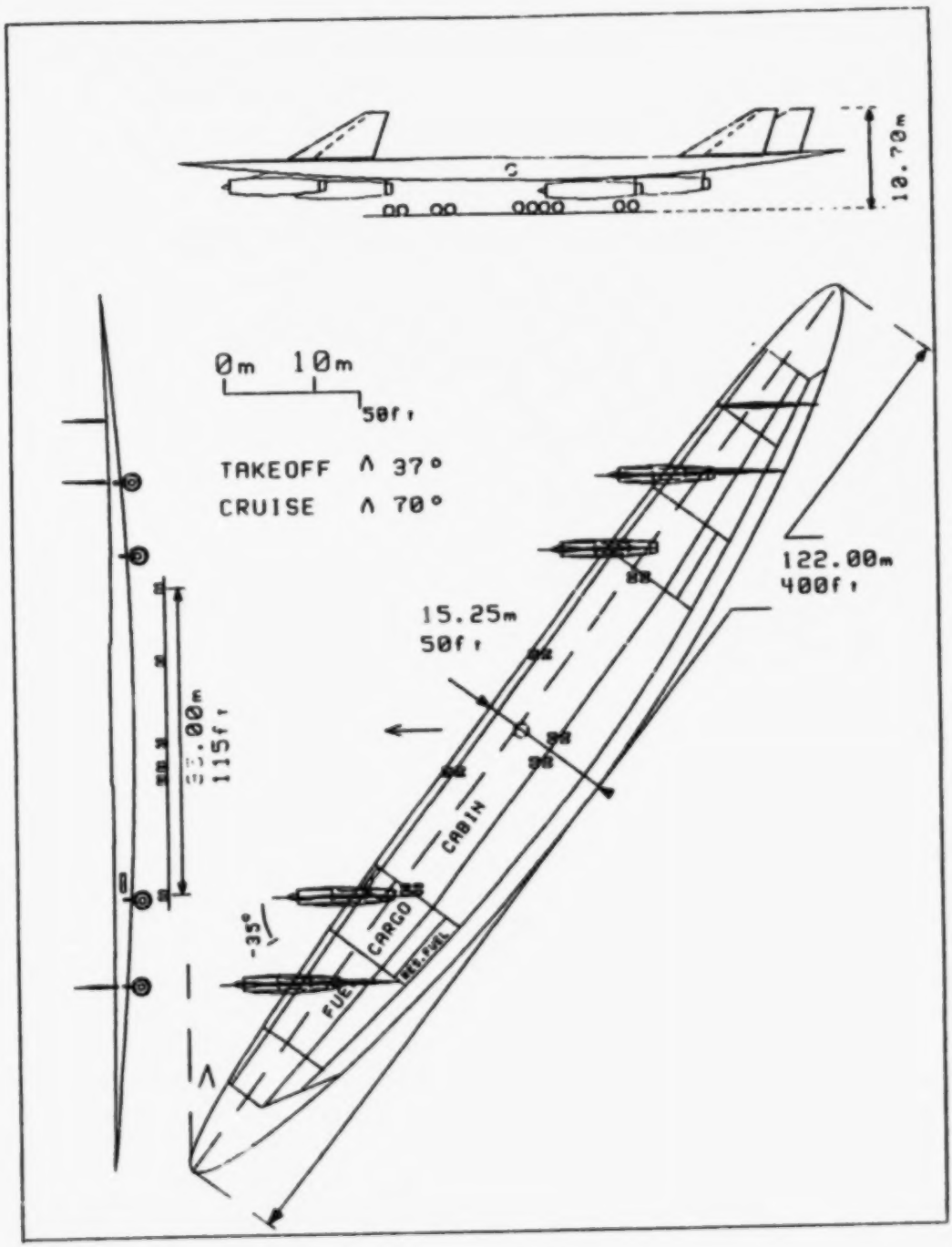


Figure 1. Oblique flying wing.

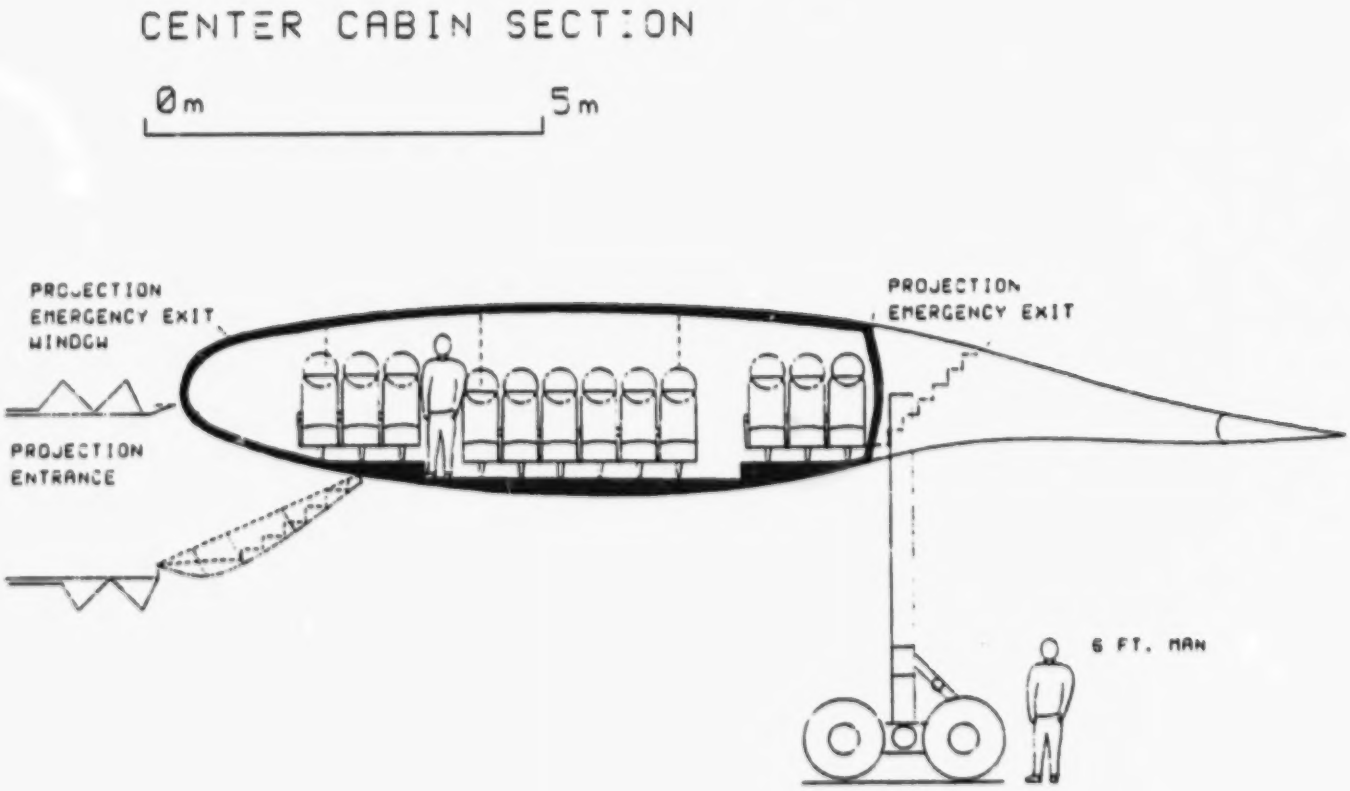


Figure 2. Cabin cross section with OFW16 airfoil.

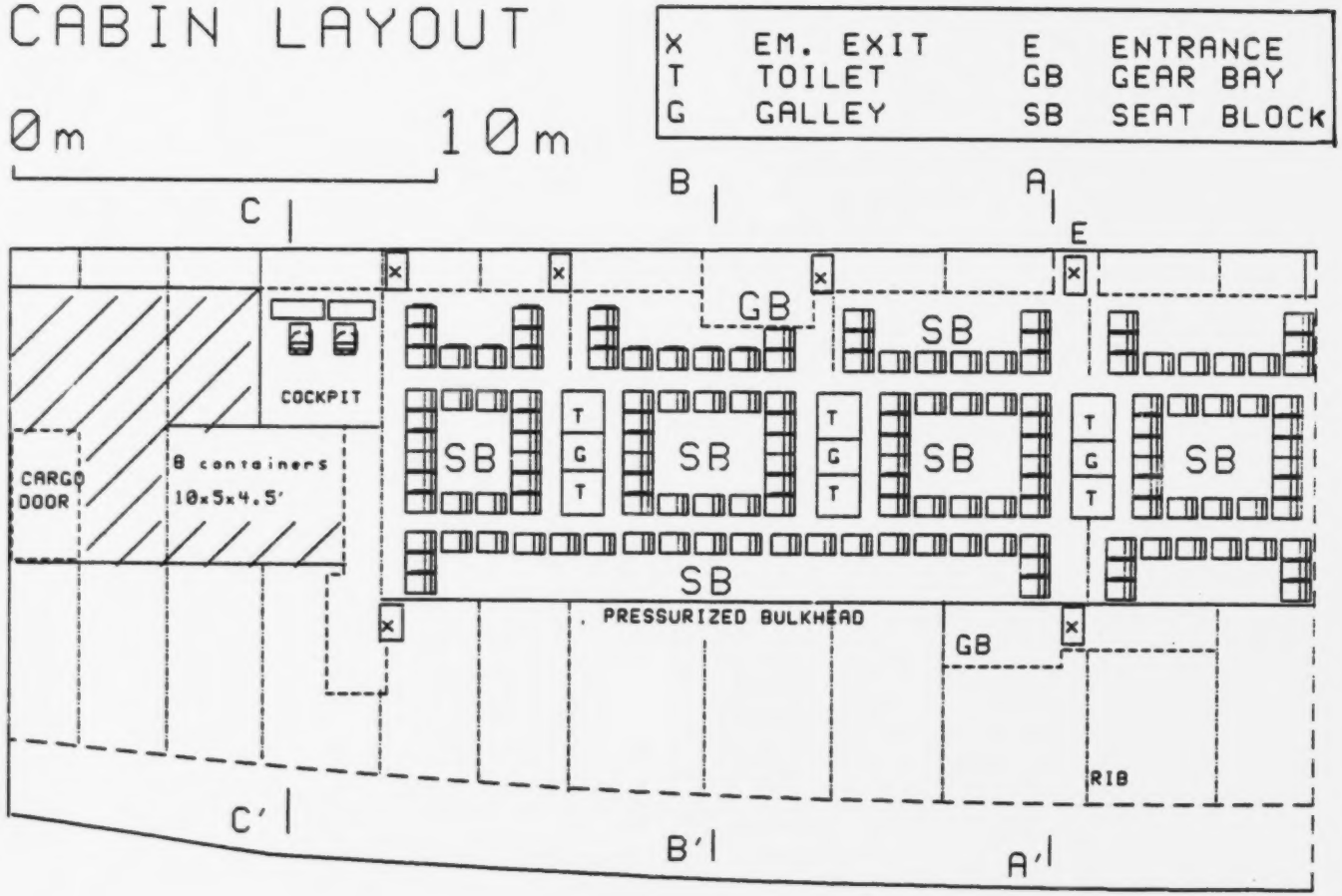


Figure 3. Passenger cabin layout.

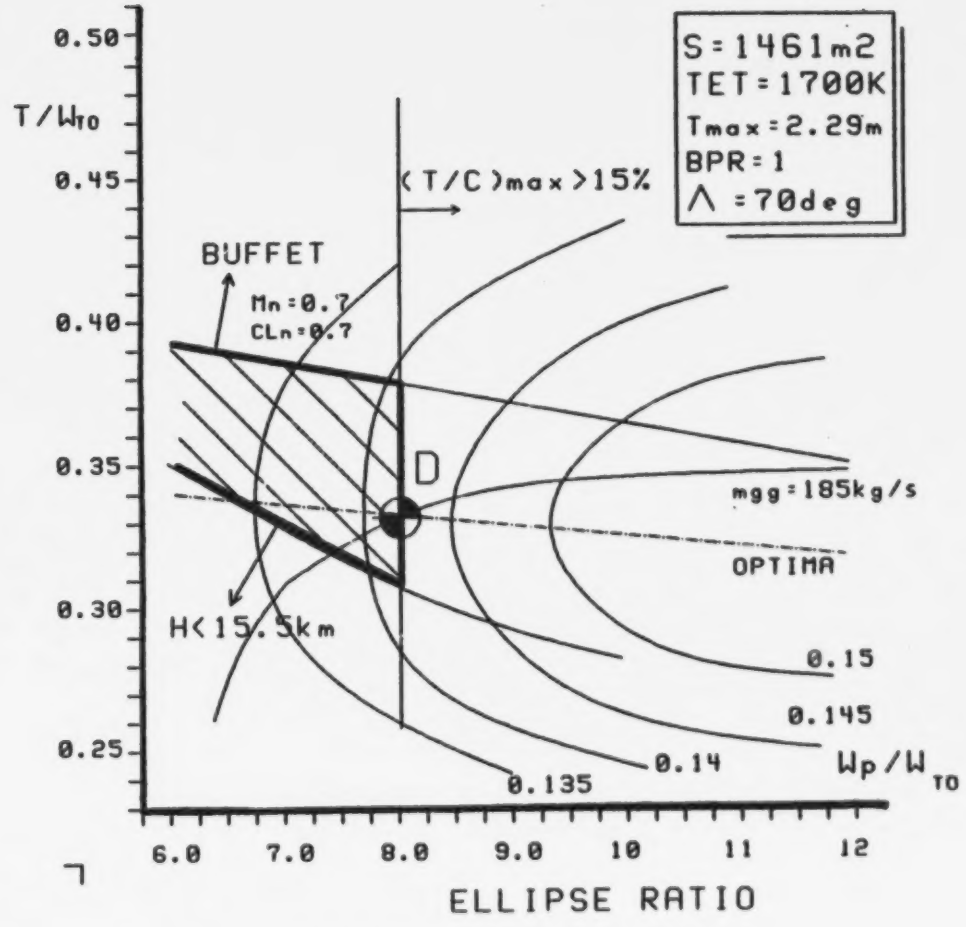


Figure 4. WING ELLIPSE RATIO AND THRUST RATIO OPTIMIZATION

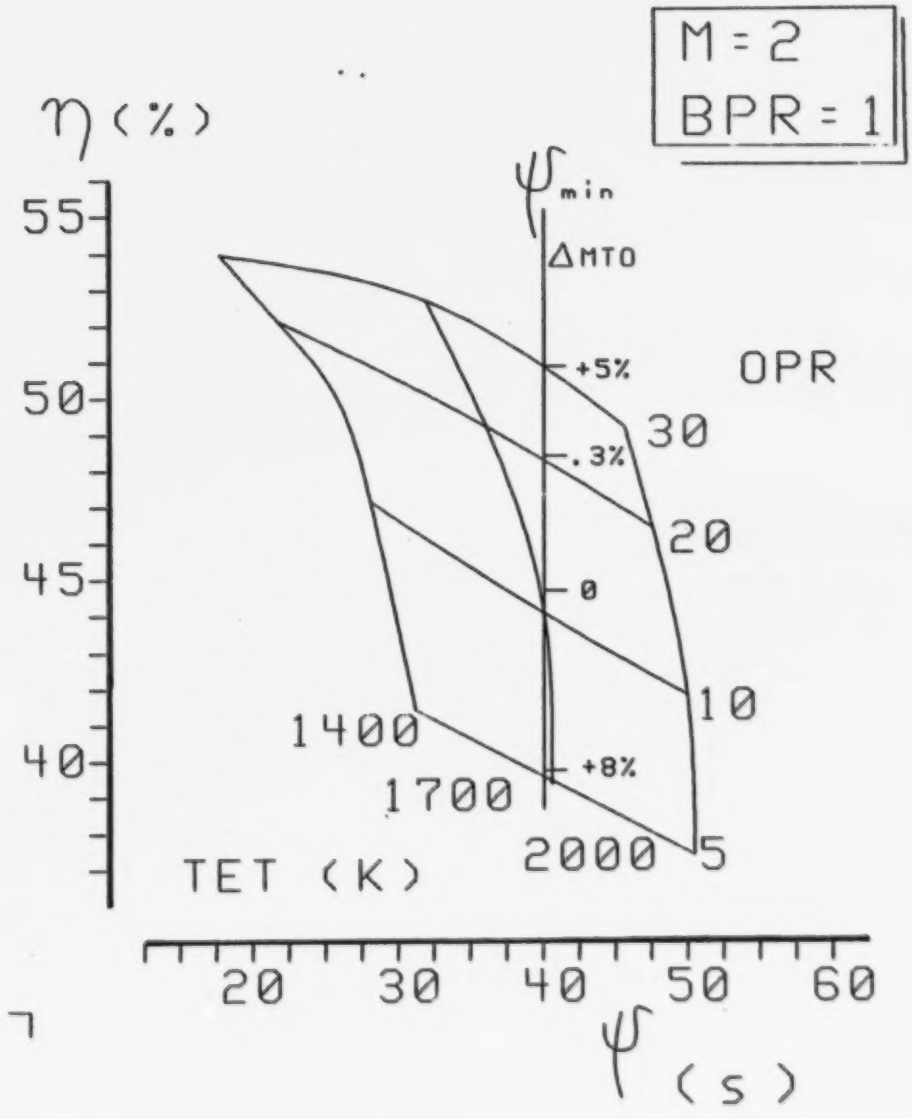


Figure 5. OPTIMIZATION OF THE ENGINE CYCLE

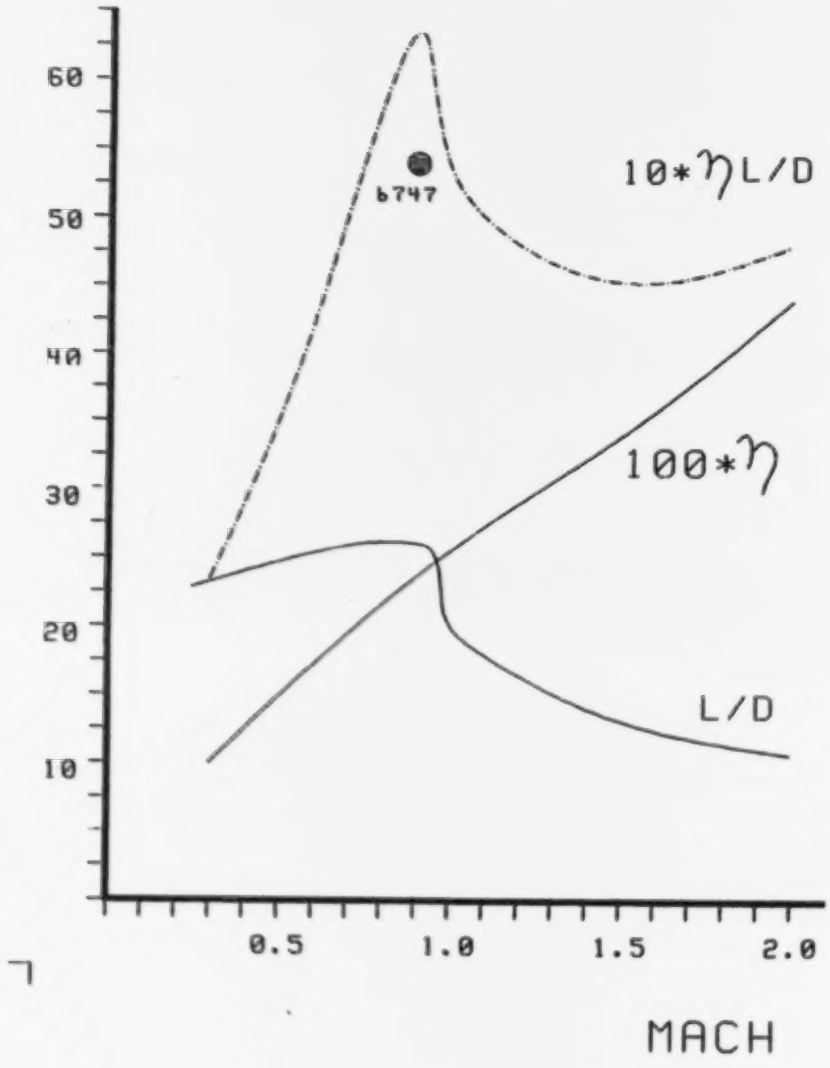


Figure 6. VARIATION OF THE MAXIMUM L/D RATIO AND THE MAXIMUM OVERALL ENGINE EFFICIENCY WITH MACH NUMBER

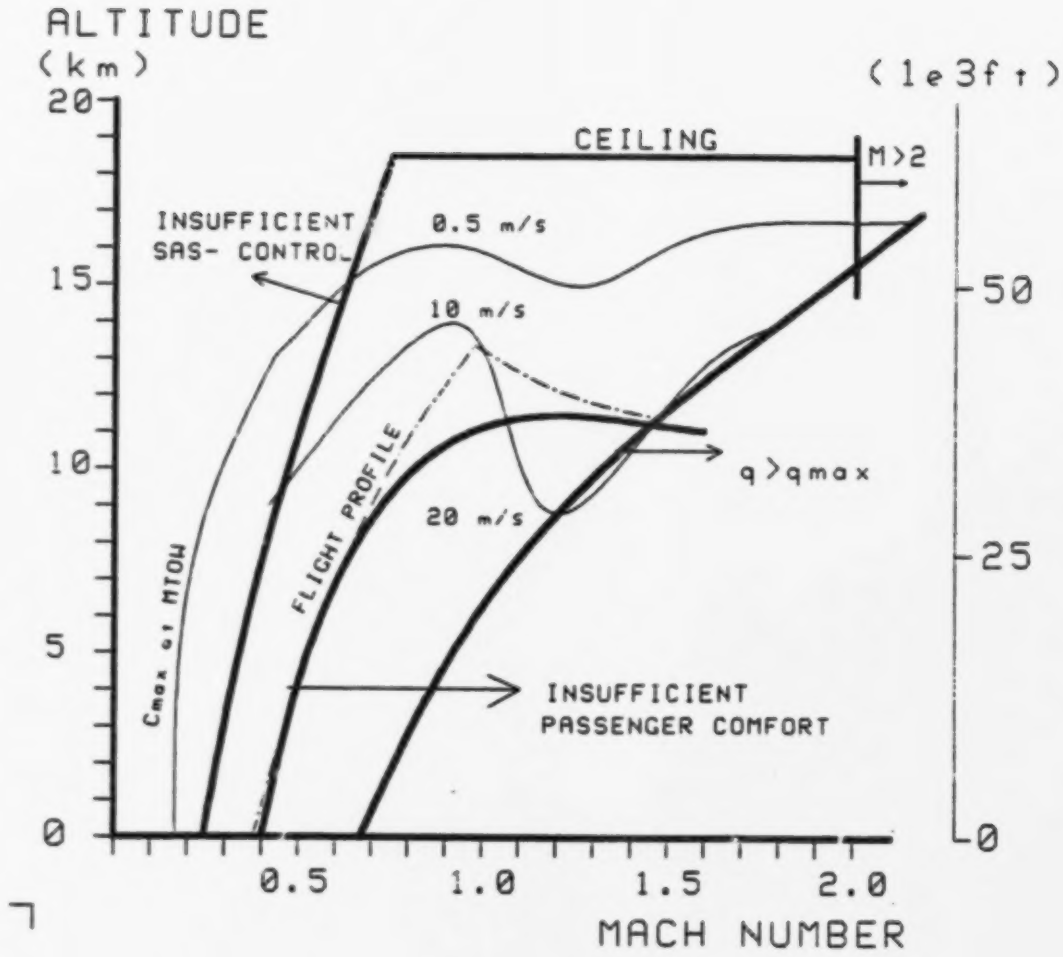


Figure 7. DESIGN ENVELOPE

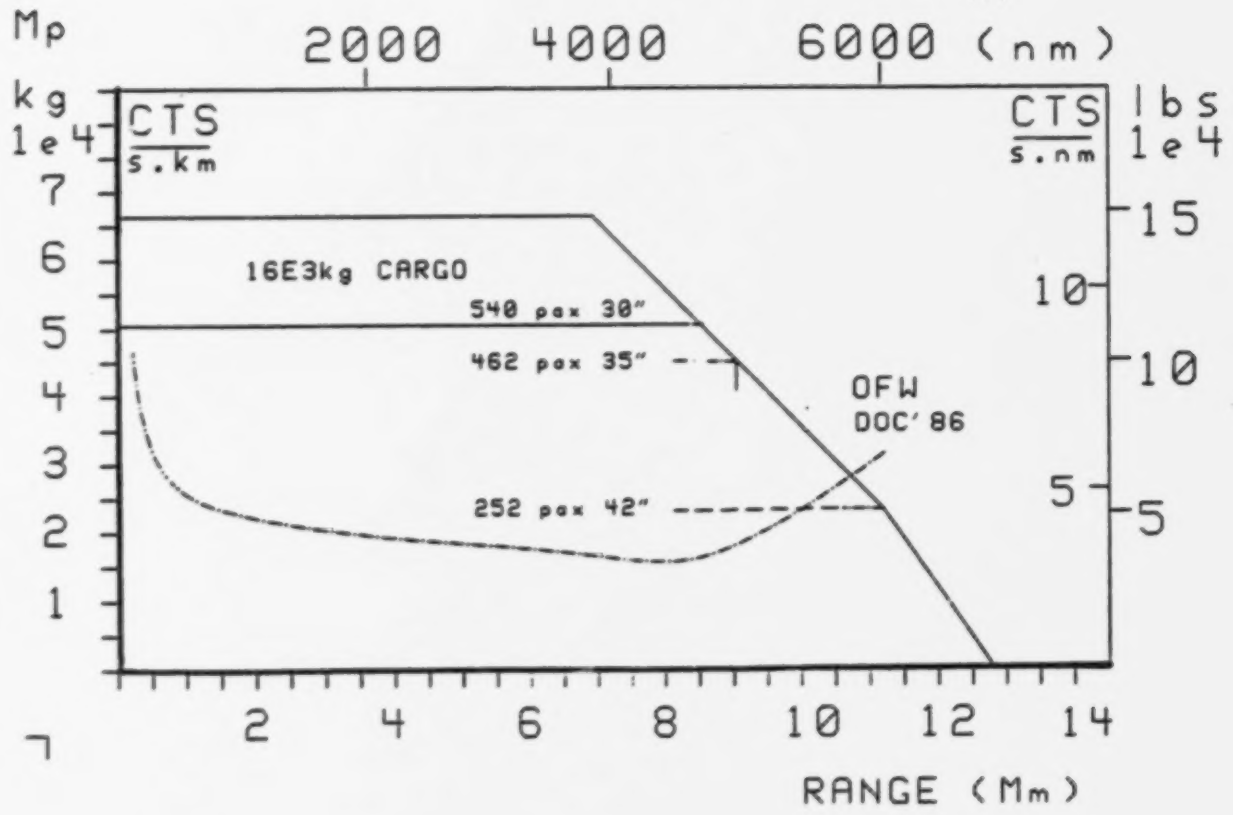


Figure 8. THE PAYLOAD RANGE DIAGRAM AND THE DIRECT OPERATING COSTS

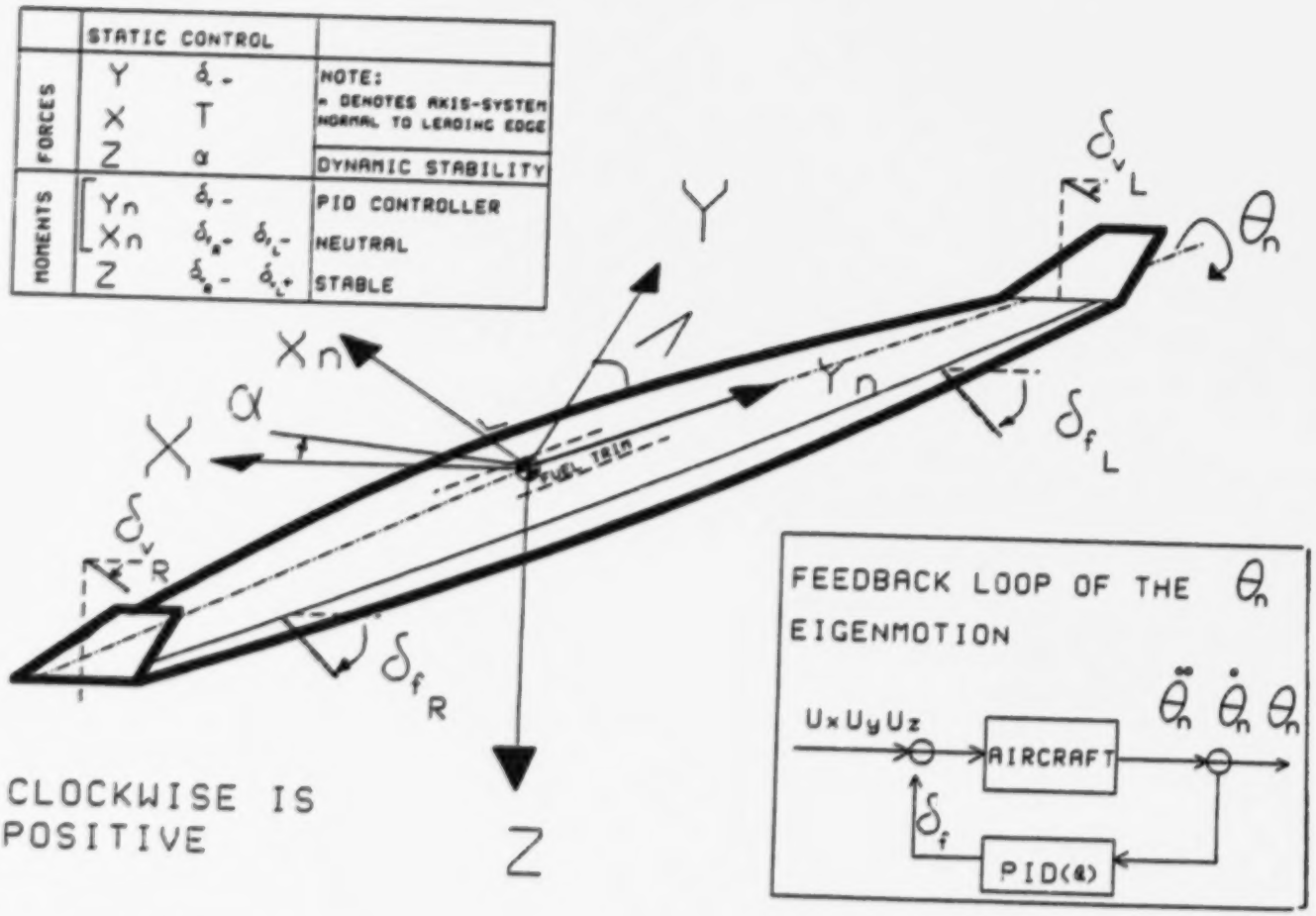


Figure 9. Stability and control of an oblique flying wing.

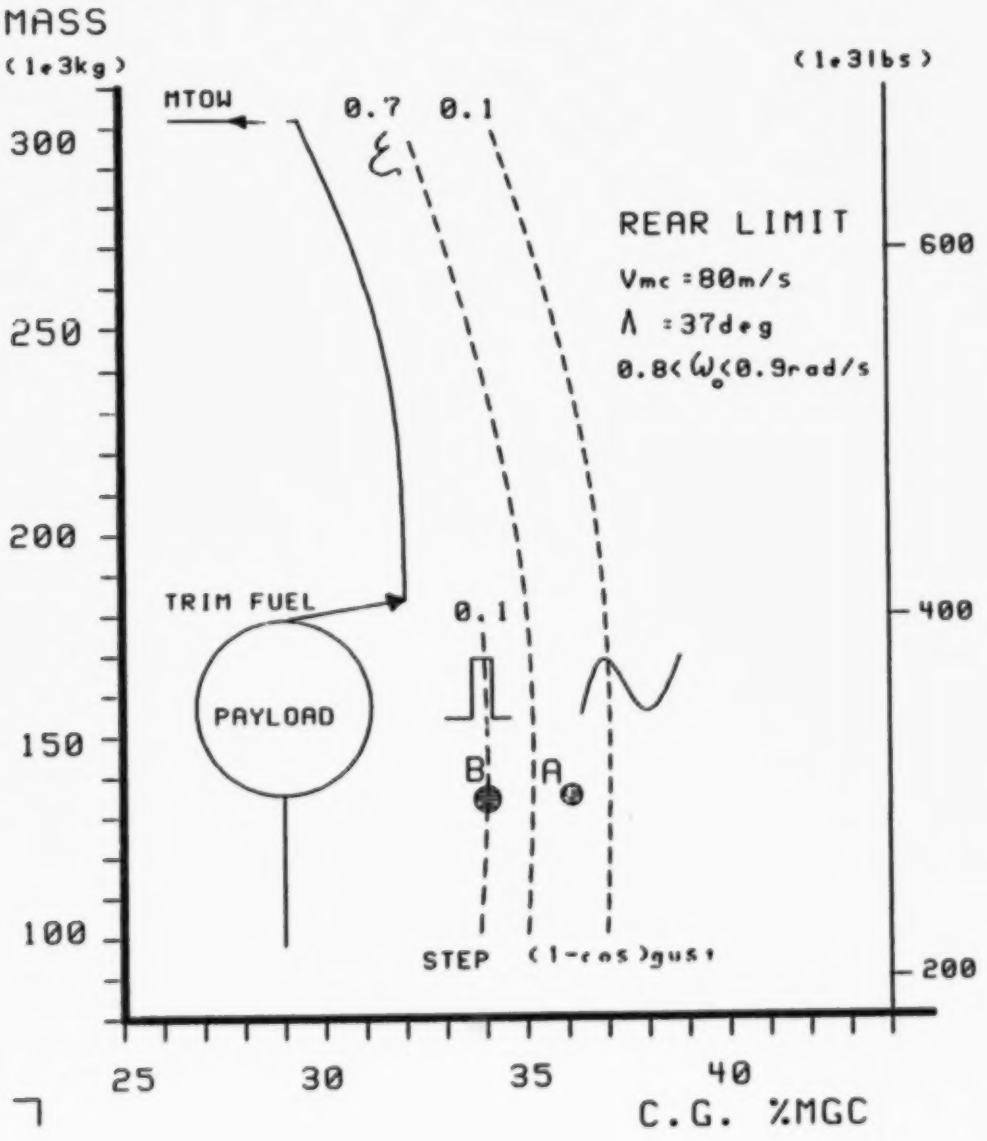
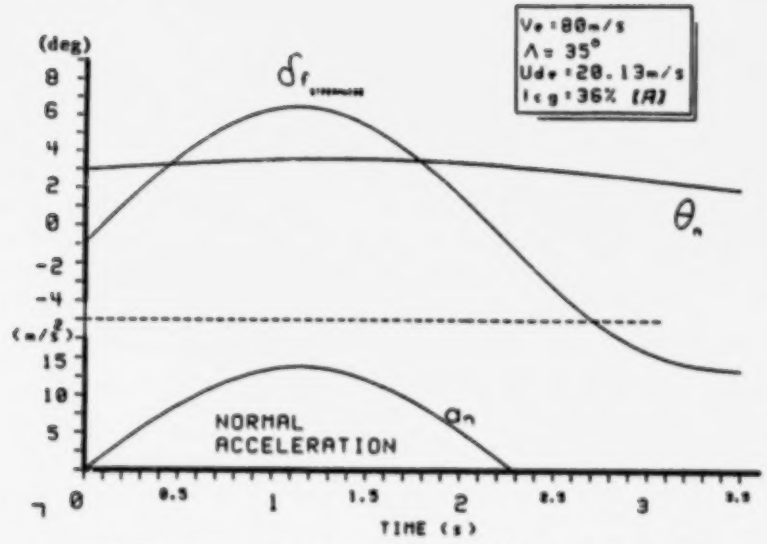


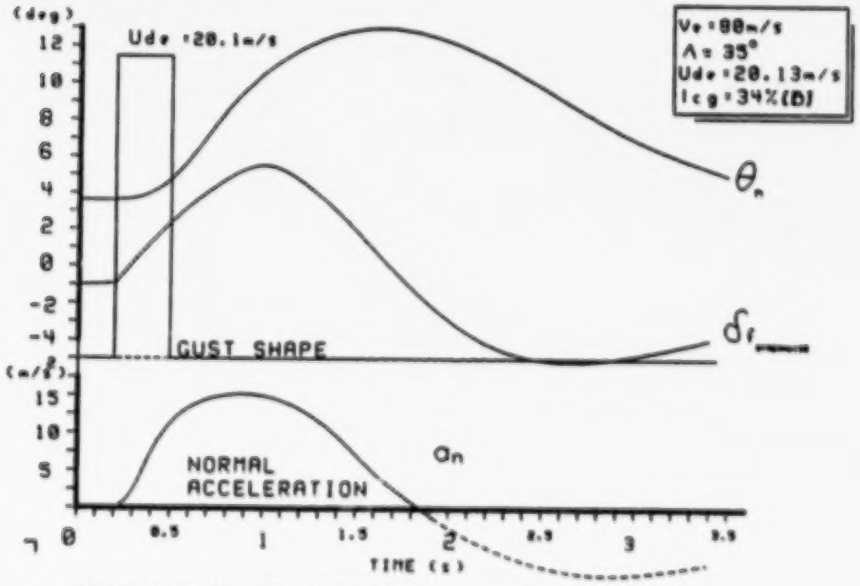
Figure 10. LOAD AND BALANCE DIAGRAM WITH CRITICAL S.A.S-LIMIT

Fig. 11a



RESPONSE TO LIMIT (1-COSINE)FAR 25 GUST

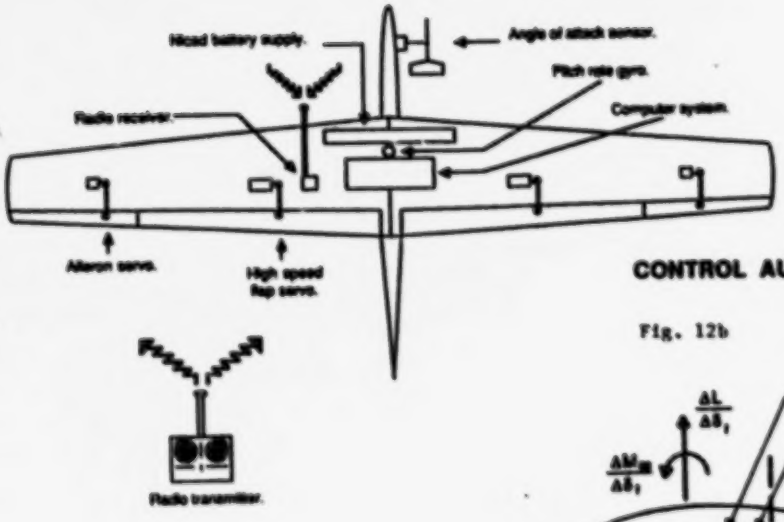
Fig. 11b



RESPONSE TO CRITICAL STEP GUST

Fig. 12a

HARDWARE LAYOUT



CONTROL AUTHORITY

Fig. 12b

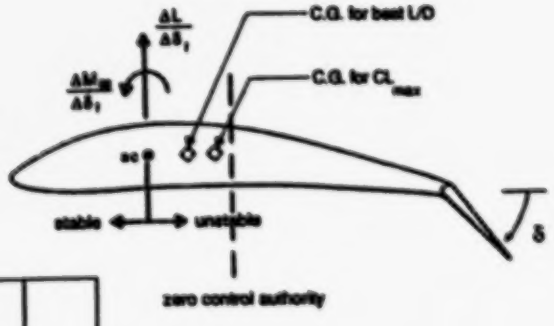
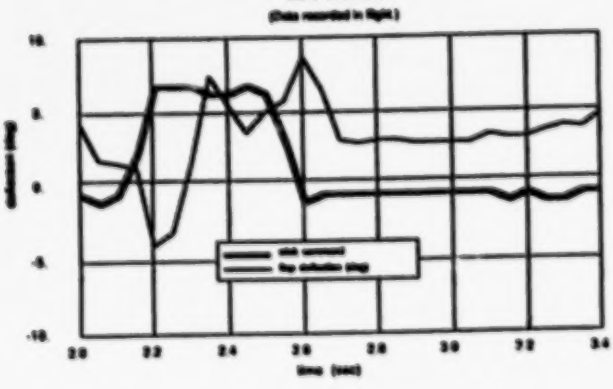


Fig. 12c **FLAP DEFLECTION vs TIME**



Test of unswept unstable flying wing control authority during summer of 1987.

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16. Abstract

This paper is based on a performance and economics study of a Mach two Oblique Flying Wing transport aircraft that is to replace the B747B. In order to fairly compare our configuration with the B747B an equal structural technology-level is assumed. It will be shown that the Oblique Flying Wing configuration will equal or outperform the B747 in speed, economy and comfort while a modern stability and control system will balance the aircraft and smooth out gusts. The aircraft is designed to comply with the FAR25 and FAR36 stage 3 noise regulations. The present design study was carried out for the Computational Fluid Dynamics division of NASA Ames Research Center.

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